Thursday, July 30, 1998
CARBONACEOUS CHONDRITES II
2:00 p.m.   Walton Theatre

Chairs: S. S. Russell
A. Greshake

Coker R. F.*   Cohen B. A.
Modeling of CM Parent Bodies

Lauretta D. S.*   Hua X.   Buseck P. R.
Mineralogy of Fine-grained Rims in the Allan Hills 81002 CM Carbonaceous Chondrite Determined by Transmission Electron Microscopy

Hua X.*   Lauretta D. S.   Buseck P. R.
Allan Hills 81002 and Lewis Cliff 90500: Paired Meteorites with Unique Fine-grained Rims

Meibom A.*   Krot A. N.
A Lithic Clast of Oxidized CV3 Material in the Reduced CV3 Chondrite Breccia Vigarano

Krot A. N.*   Todd C. S.
Metal-Carbide-Magnetite-Fayalite Association in a Bali-like Clast in the Reduced CV3 Chondrite Breccia Vigarano

Hutcheon I. D.*   Krot A. N.   Keil K.   Phinney D. L.   Scott E. R. D.
Manganese-53/Chromium-53 Dating of Fayalite in Mokoia: Evidence for Asteroidal Alteration of CV Chondrites

Nazarov M. A.   Kurat G.*   Brandstätter F.
Silica-bearing Objects in Bali (CV3): A Novel Type of Inclusion in Carbonaceous Chondrites

Wang M.-S.   Socki R.   Zolensky M. E.*   Lipschutz M. E.
Thermal Metamorphism of Carbonaceous Chondrites: Simulations and Reality

Bell M. S.*   Zolensky M. E.   Yang S. V.
Evidence for Thermal Alteration in the Asuka 881655 Chondrite

Tomeoka K.*   Yamahana Y.   Sekine T.
Experimental Shock Metamorphism of the Murchison CM Carbonaceous Chondrite

Korochantsev A. V.*   Badjukov D. D.
Chondritic Carbonaceous Materials: Terrestrial Analogs and Their Shock Modification

Keller L. P.*
Planar Defects in Matrix Olivines from the Oxidized Subgroup of the CV3 Carbonaceous Chondrites: A Group Characteristic

MODELING OF CM PARENT BODIES. R. F. Coker[1] and B. A. Cohen[2], [1]Department of Physics, University of Arizona, Tucson AZ 85721 (rfc@physics.arizona.edu), [2]Department of Planetary Sciences, University of Arizona, Tucson AZ 85721 (bcohen@lpl.arizona.edu).

We have constructed an asteroid model with the intent of tracking the radial and temporal dependence of temperature and composition throughout a 100-km diameter body, with emphasis on constraining the temperature and duration of a liquid water phase. The asteroid is composed of rock (altered and unaltered), water (ice or liquid), and void spaces. Thermal properties of the materials are composition- and temperature-dependent where appropriate. The initial distribution of materials is uniform, except for a small surface regolith, and can be varied for different calculations. We investigate the effects of formation distance, formation time since solar nebula collapse, hydration reactions, and water, void, and rock content and composition on the evolution of the asteroid.

The numerical scheme we employ to handle the spherically-symmetric heat flow equation is similar to that used by [1]. We also make some of the same assumptions: accretion is rapid, the rock is fully lithified, there are no pressure dependencies of the material properties, and the major heat source is radioactivity. We incorporate a suite of both long- and short-lived radionuclides, the abundances of which we obtained from [2].

Our model differs significantly from [1] in some ways. First, we explicitly add a regolith to the asteroid, which for our purposes is a zone of a few hundred meters where porosity increases and water content decreases dramatically. The impact processes which create such a regolith proceed over the timescale of the solar system, so our constant regolith overestimates its own effects on the evolution of the interior. However, we find that the regolith can act either as a thermal blanket or a thermal sink, depending on the initial setup. Second, we include solar nebula temperature evolution [3] to determine the initial asteroid temperature as well as the surface equilibrium temperature; at 10^7 years after nebula collapse, the nebula dissipates and the surface is assumed to be in thermal equilibrium with the solar flux. This produces a substantial difference between our models, because many material properties are dependent on temperature and the nebula at 3 AU drops to ~20K before it dissipates. Third, we vary the time between nebular collapse and the accretion of the asteroid. This is similar to varying the amount of live ^{26}Al as in [1], but has wider implications because of the solar nebula model discussed above. Fourth, we consider a broad set of alteration reactions and use a finite rate of reaction. This allows us to track effects of mineral alteration on water salinity, pH, and freezing-point depression. The choice of alteration reaction determines the amount of heat released during alteration, and this is found to have a large effect on the duration of liquid water. The choice of reaction also has volumetric consequences; we suggest that examination of altered matrix for expansion textures might constrain the mode of alteration.

Although highly dependent on the choice of alteration reaction, our preliminary results show that the interior of a 100-km-diameter body can reach temperatures high enough to produce liquid water for significant times (>10^6 years). Some scenarios allow the complete melting of ice in the deep interior, with a subsequent temperature rise (T_{max}≈400K). We produce a nonuniform distribution where liquid water persists longest in the deepest zones and the regolith never sees conditions appropriate to aqueous alteration. The nonuniform liquid distribution produces a radially-dependent amount of alteration products. It has been suggested [4] that both CI- and CM-type material could be formed by progressively altering the same initial assemblage, perhaps by this kind of parent-body history.

References: [1]Grimm R. E. and McSween H. Y. (1989) *Icarus, 82,* 244–280. [2]Anders E. and Ebihara M. (1982) *GCA, 46,* 2363–2380. [3]Cassen P. (1994) *Icarus, 112,* 405–429. [4]Zolensky M. E., Bourcier W. L., and Gooding J. L. (1989) *Icarus, 78,* 411–425.

MINERALOGY OF FINE-GRAINED RIMS IN THE ALH-81002 CM CARBONACEOUS CHONDRITE DETERMINED BY TRANSMISSION ELECTRON MICROSCOPY. D. S. Lauretta, X. Hua, and P. R. Buseck. Departments of Geology and Chemistry & Biochemistry, Arizona State University, Tempe AZ 85287-1404, USA (dante.lauretta@asu.edu).

Introduction: CM carbonaceous chondrites are chemically primitive meteorites that consist of coarse-grained, high-temperature components embedded within fine-grained matrix. Even finer-grained, matrixlike material occurs as distinct rims surrounding coarse-grained objects. The relationship between the fine-grained rims and bulk matrix is uncertain. It has been suggested that the rims are solar nebula condensates and that matrix is derived from these rims by regolith gardening [1]. Other workers suggest that matrix and rims are mineralogically distinct [2]. In order to resolve these issues it is necessary to characterize the mineralogy of these fine-grained rims. We initiated a mineralogical survey of these objects using transmission electron microscopy (TEM) to complement our chemical and petrographic studies [3]. We report initial observations of the mineralogy of fine-grained rims in the CM chondrite ALH-81002.

Analytical Methods: Electron-transparent specimens were prepared using a precision ion-milling system. Compositions were determined with a Phillips 400-ST-FEG TEM equipped for energy-dispersive spectroscopy (EDS). High-resolution images were obtained on a JEOL 4000EX TEM. Mineral phases were identified by correlating electron-diffraction patterns and high-resolution images with chemical data.

Results: The rim that we investigated surrounds a porphyritic olivine chondrule. Its thickness varies between 200 and 300 µm. Grain sizes in the rim range from 4 to 200 nm in diameter. The most abundant phase is rich in Fe and Si. Electron-diffraction patterns, high-resolution images, and its composition suggest that it is cronstedtite, the Fe-rich endmember of serpentine. We also observed a Si- and Mg-bearing phase that yields electron-diffraction data consistent with forsteritic olivine. Nickel and S abundances correlate in both EDS and electron microprobe data [3], suggesting a Ni-bearing sulfide such as the monosulfide solid solution or pentlandite. A second S-bearing, Ca-rich phase was also observed. The d-spacings obtained from electron-diffraction patterns suggest that it is gypsum.

Discussion: The mineral phases in the fine-grained rims in ALH-81002 are unequilibrated. The most abundant phase is Fe-rich serpentine, most likely cronstedtite. It coexists with forsteritic olivine. Chemical data indicate the presence of Ni-bearing sulfides. Gypsum, hydrated calcium sulfate, is also present. Thus, these fine-grained rims contain material that formed under different oxygen fugacities and experienced different degrees of aqueous alteration. Work is under way to characterize their mineralogy in greater detail and to determine their origin.

Acknowledgments: This work was supported by NASA grant NAG5-4308. We thank K. Weiss and J. Wheatley for technical assistance and F. Camara, M. Posfai, and L. Garvie for helpful discussions. The sample of ALH-81002 was provided by the NASA Antarctic Meteorite Working Group.

References: [1] Metzler et al. (1992) *GCA, 56*, 2873–2897. [2] Zolensky et al. (1993) *GCA, 57*, 3123–3148. [3] Hua et al. (1998) this volume.

ALH81002 AND LEW90500: PAIRED METEORITES WITH UNIQUE FINE-GRAINED RIMS. X. Hua, D. S. Lauretta, and P. R. Buseck, Departments of Geology and Chemistry & Biochemistry, Arizona State University, Tempe AZ 85287-1404, USA (huaxin@asu.edu).

Introduction: Antarctic CM meteorites ALH81002 and LEW90500 contain abundant fine-grained rims (FGRs) that surround a variety of coarse-grained objects. Detailed petrographic and chemical studies reveal that rims from both meteorites have identical bulk compositions, regardless of what minerals are enclosed. The chemistry and grain-size distribution of FGRs are homogeneous at the 10-µm scale. We conclude that ALH81002 and LEW90500 are either paired fragments of a single meteorite, even though they were collected 875 km from each other, or are genetically related.

Petrography and mineral chemistry: Fine-grained materials occur as rims around all type of coarse-grained objects in these two Antarctic meteorites. Rim thicknesses differ from object to object and reach up to several hundred micrometers. We checked 23 objects and their surrounding FGRs using BSE imaging. The objects include (1) porphyritic olivine chondrules (both FeO-rich and FeO-poor); (2) barred olivine chondrules (both FeO-rich and FeO-poor); (3) microporphyritic olivine chondrules (FeO-poor); (4) olivine crystals (end-member forsterite, ~Fa50, and zoned fayalitic olivines); (5) fayalitic olivine grains coexisting with apatite; (6) PCP; (7) calcite crystals with outer tochilinite rings; and (8) calcite grains intergrown with spinel and perovskite. All FGRs have similar porous appearances and contain fine anhedral crystals of silicates, sulfides, and metal. Although the host objects are irregularly shaped, the overall rim appearances are smooth and round with rim materials filling in embayed areas and thinning over prominences. TEM observation on ALH81002 reveals grains 4–200 nm in size [1].

Bulk abundances of major (Si, Mg, S, Fe) and minor (Na, Al, Cr, P, and Ni) elements have been determined for 90 spots from 15 FGRs using an electron microprobe with a 10-µm beam. All rims in both meteorites have identical bulk compositions, although the compositions of their enclosed core materials differ dramatically. Except for Fe, the standard deviation of the abundance of 13 measured elements is below 1%. This variation in Fe abundance can be interpreted as heterogeneous distribution of large grains (>1 µm) of metal or Fe sulfides. Elemental totals of the rims are only 76.4 wt% for ALH81002 and 77.6 wt% for LEW90500. These low totals are consistent with their porous appearance but may also be the result of high water or C contents. The FGRs clearly show beam damage after EMPA analysis.

Discussion and Conclusion: The compositions of FGRs in CCs normally differ from meteorite to meteorite, from rim to rim within the same meteorite, and even from layer to layer within the same rim [2-4]. In contrast, the FGRs in ALH81002 and LEW90500 are chemically homogeneous. This uniformity indicates these two Antarctic meteorites are either paired or genetically related. If they are paired then this will be the first set collected from such widely separated locations. In addition, rim thicknesses depend on the topography of their enclosed objects rather than their compositions, suggesting that these rims formed by dust accretion rather than by alteration of their enclosed objects.

Acknowledgments: This work was supported by NASA grant NAG5-4308. The ALH81002 and LEW90500 samples were provided by the NASA Meteorite Working Group.

References: [1] Lauretta et al. (1998) this volume. [2] McSween (1987) *GCA, 51,* 2469–2477. [3] Metzler et al. (1992) *GCA, 56,* 2873–2897. [4] Hua et al. (1996) *GCA, 60,* 4265–4274.

A LITHIC CLAST OF OXIDIZED CV3 MATERIAL IN THE REDUCED CV3 CHONDRITE BRECCIA VIGARANO. Anders Meibom and Alexander N. Krot HIGP/SOEST, University of Hawai'i, Honolulu, HI 96822, USA (meibom@pgd.hawaii.edu).

Introduction: The modal metal/magnetite ratios and Ni contents of metal and sulfides led McSween [1] to divide CV chondrites into reduced and oxidized subgroups. Based on mineralogical criteria, Weisberg et al. [2] subdivided oxidized CVs into the Bali-like and Allende-like subgroups: matrix olivine in the Allende-like subgroup has a more restricted compositional range (Fa_{30-60} *vs*. Fa_{10-90}) and a lower matrix abundances (0.6-0.7 *vs.* 0.7-1.2) than in the Bali-like subgroup; phyllosilicates are less abundant; fayalite (Fa_{90-100}) is absent. Krot et al. [3,4] showed that these differences resulted from late stage alteration. E.g., in Type I chondrules in the Bali-like chondrites phyllosilicates replace pyroxenes and mesostases and fayalite replaces magnetite. In Type I chondrules in the Allende-like chondrites mesostases are replaced by nepheline and sodalite; chondrule phenocrysts and magnetite are rimmed, veined and replaced by ferrous olivine (Fa_{40-50}) [3-5]. Two kind of models have been proposed to explain this alteration: **a**) high-temperature gas-solid reactions in the oxidized solar nebula [2,6] and **b**) low-temperature fluid-rock reactions in the presence of aqueous solutions in the CV asteroid [3-5].

The reduced CV chondrite Vigarano is a regolith breccia [8] containing adjacent oxidized and reduced opaque assemblages [1] and phyllosilicates scattered in the matrix [9]. Some chondrules and CAIs show alteration features similar to those in the Allende-like CVs [7,10] and matrix regions contain lath-shaped ferrous olivine [2] and secondary Ca-Fe-rich silicates [5]. Based on these observations, Krot et al. [4,5] suggested that mixing of reduced (unaltered) and oxidized (altered) components is due to brecciation of the heterogeneously-altered CV asteroid. On the contrary, Weisberg et al. [2] interpreted this as evidence for mixing in the nebula prior to lithification. Here we describe a lithic clast of oxidized material in Vigarano.

Results: The clast is found in thin sections JSC-1, 3, and 5; kindly provided by M. E. Zolensky. It measures ~1x0.5 cm and is composed of Type I chondrules surrounded by coarse-grained and fine-grained rims, opaque matrix, and rare CAIs. Matrix/chondrule ratio is ~ 1.1. Matrix consists of fine-grained (< 1 µm) ferrous olivine, large (up to 100 µm) anhedral fayalite grains (Fa_{80-100}), rounded objects (20-50 µm in diameter) of porous Ca-Fe-rich pyroxenes ($Fs_{10-50}Wo_{50}$), Ni-poor sulfide, Ni- and Co-rich metal, and possibly phyllosilicates; magnetite is virtually absent; clastic fragments are rare. Opaque nodules in Type I chondrules consist of magnetite, Ni-rich metal, Ni-poor sulfide and rare pentlandite; relic kamacite grains occur only as inclusions in chondrule phenocrysts. Magnetite is replaced to various degrees by fayalite (Fa_{90-100}). Ca-rich rims composed of salite-hedenbergite pyroxenes ($Fs_{10-50}Wo_{50}$) surround a few chondrules. Several individual chondrules in the host Vigarano show similar alteration features.

Conclusion: Based on the presence of the lithified clast of Bali-like material, individual chondrules and CAIs of Bali-like [11, this study] and Allende-like [2,7,10] material in Vigarano, we infer that the reduced and oxidized materials are different lithological varieties of the heterogeneously-altered CV asteroid mixed during regolith gardening. This process is analogous to the formation genomict breccias among ordinary, enstatite, and carbonaceous chondrites [12,13,14].

References: [1] H. McSween (1978) *GCA, 41,* 1777; [2] M. Weisberg et al. *M&PS, 32,* A138; [3] A. Krot et al. (1998a) *M&PS, 33,* in press; [4] A. Krot et al. (1998b) *M&PS, 33*, in press; [5] A. Krot et al. (1995) *Meteoritics, 30,* 748; [6] H. Palme & D. Wark (1988) *LPS, 19*, 897; [7] M. Kimura & Y. Ikeda (1996) *M&PS, 31*, A70; [8] E. Mazor et al. (1970) *GCA, 34*, 781; [9] A. Graham & M. Lee (1992) *LPS, 18*, 435; [10] P. Sylvester et al. (1993) *GCA, 57,* 3763; [11] A. Krot (1998) this issue; [12] E. Scott et al. (1985) *JGR suppl. 90, D137*;. [13] A. Rubin (1990) *GCA, 54, 1217*. [14] K. Metzler et al., (1992) *GCA 56, 2873*.

METAL-CARBIDE-MAGNETITE-FAYALITE ASSOCIATION IN A BALI-LIKE CLAST IN THE REDUCED CV3 CHONDRITE BRECCIA VIGARANO. A. N. Krot and C. S. Todd, Hawai'i Institute Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai'i, Honolulu HI 96822, USA (sasha@pgd.hawaii.edu).

Introduction: CV3 chondrites are a mineralogically diverse group of meteorites that is divided into reduced and oxidized, Bali-like and Allende-like, subgroups [1,2]. The major differences between these subgroups resulted from late-stage alteration [3]. In the Bali-like chondrites this alteration formed phyllosilicates, magnetite, Ni-rich metal and sulfides, fayalite ($Fa_{>90}$), and Ca-Fe-rich silicates. Although Vigarano is typically classified as a reduced CV chondrite [2], it contains chondritic clasts of the Bali-like materials indicating mixing of the reduced and oxidized materials during regolith gardening [4; this study]. In this paper, we describe assemblage of metal-sulfide-carbide-magnetite-fayalite in a Bali-like clast in the Vigarano thin section 477–7, kindly provided by C. Perron. This is the first discovery of Fe,Ni-carbides in CV chondrites that has important implications for the origin of pure fayalite.

Results: Metal-sulfide-carbide-magnetite-fayalite assemblages are observed in chondrules, fine-grained rims and matrix in the Bali-like clast. Magnetite replaces metal-sulfide-carbide nodules. The anhedral and subhedral fayalite ($Fa_{90–100}$) grains (up to 100 µm in size) replace metal and magnetite; relic magnetite grains occur as inclusions in fayalite. Magnetite has near pure composition (<0.2 wt.% Ni); sulfides are Ni-poor (<0.1 wt% Ni); pentlandite (18 wt.% Ni) is very rare. Metal consists of Ni-rich taenite (46 ± 2 wt.% Ni; 1.8 ± 0.2 wt.% Co); kamacite nodules are preserved only inside chondrule phenocrysts. There are two types of carbides in the clasts: dominant, Ni-poor (1.8 ± 0.2 wt.% Ni; 0.4 ± 0.1 wt.% Co) and rare, Ni-rich (4.9 wt.% Ni).

Discussion: Fe,Ni-carbides in association with metal, sulfides and magnetite have been previously described in the least metamorphosed type 3 ordinary and CO chondrites [5–9]. Although these carbide-bearing assemblages were originally interpreted as gas-solid nebular products [5–7], we showed [8] that cohenite [$(Fe,Ni)_3C$] will not form under equilibrium conditions in the nebulae: $3Fe(s) + CO(g) + H_2(g) = Fe_3C(s) + H_2O(g)$ {r1}. Mineralogical observations and thermodynamic analysis favor parent body formation of carbides below 700 K [8], $15Fe(s) + 4CO(g) = 4Fe_3C(s) + Fe_3O_4(s)$ {r2}; $3Fe(s) + 2CO(g) = Fe_3C(s) + CO_2(g)$ {r3}. This conclusion is supported by TEM study of matrix carbides in Semarkona which consist of fine-scale lamellae intergrowths of cohenite and χ-carbide [$(Fe,Ni)_5C_2$] [9]. Although magnetite can be formed below 400 K in a canonical solar nebula, $3Fe(s)+4H_2O(g) = Fe_3O_4(s)+4H_2(g)$ {r4}, mineralogical observations [8] and large range in $\delta^{18}O$ (~13 ‰) in Semarkona magnetites [10] favor its asteroidal formation: {r2}; $Fe_3C(s) + 5H_2O(g) = Fe_3O_4(s) + CO(g) + 4H_2(g)$ {r5}. TEM and O-isotope data are absent for the carbide-magnetite assemblages in Vigarano, but the mineralogical similarities between these assemblages and those in Semarkona, and thermodynamic analysis [8] favor asteroidal formation {r3–5}.

Two models have been proposed to explain the origin of fayalite in the Bali-like chondrites Kaba and Mokoia [11]. Hua et al. [11] concluded that fayalite formed by high-temperature gas-solid nebular reactions (>1000°C) between SiO gas, produced by decomposition of pyroxene: $2MgSiO_3(s)+H_2(g) = Mg_2SiO_4(s)+SiO(g)+H_2O(g)$ {r6}, and magnetite: $2Fe_3O_4(s)+3SiO(g)+H_2O(g) = 3Fe_2SiO_4(s)+H_2(g)$ {r7}. In contrast, Krot et al. [12] suggested low temperature (<300°C) formation of fayalite in the presence of aqueous solution in an asteroidal environment: $2Fe_3O_4(s)+3SiO_2(aq)+2H_2(g) = 3Fe_2SiO_4(s)+2H_2O(g)$ {r8}. Because fayalite replaces magnetite that post-dates carbide formation, we infer that fayalite formed in asteroidal setting {r8}. Presence of fayalite veins crosscutting fine-grained rims and matrices in Kaba, Mokoia [12] and Bali-like clasts in Vigarano [4, this study] and Mn-Cr systematics of fayalite grains in Type I chondrules in Mokoia [13] support this conclusion.

References: [1] McSween H. Y. (1978) *GCA, 41,* 1777. [2] Weisberg M. K. et al. (1997) *Meteoritics and Planet. Sci., 32,* A138. [3] Krot A. N. et al. (1998) *Meteoritics and Planet. Sci., 33,* in press. [4] Meibom A. and Krot A. N. (1998) this volume. [5] Hutchison R. et al. (1987) *GCA, 51,* 1875. [6] Alexander C. M. O'D.et al. (1989) *GCA, 53,* 3045. [7] Taylor G. J. et al. (1981) *LPS XXII,* 1076. [8] Krot A. N. et al. (1997) *GCA, 61,* 219. [9] Keller L. (1997) *Meteoritics and Planet. Sci., 32,* A70. [10] Choi B.-G. (1998) *Nature,* in press. [11] Hua X. et al. (1995) *GCA, 59,* 563. [12] Krot A. N. et al. (1997) *Meteoritics &Planet. Sci., 32,* A75. [13] Hutcheon I. D. et al. (1998) this volume.

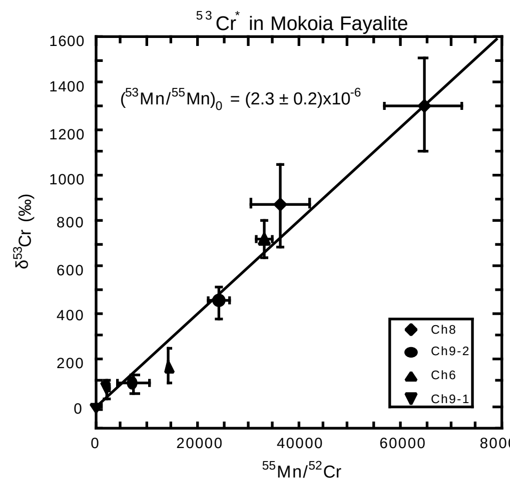
MANGANESE-53–CHROMIUM-53 DATING OF FAYALITE IN MOKOIA: EVIDENCE FOR ASTEROIDAL ALTANDRATION OF CV CHONDRITES. I. D. Hutcheon[1], A. N. Krot[2], Klaus Keil[2], D. L. Phinney[1], & E. R. D. Scott[2], [1]Lawrence Livermore National Laboratory, Livermore, CA 94551; [2]Hawai'i Institue for Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai'i, Honolulu, HI 96822, USA

The CV chondrites experienced several alteration processes which produced secondary mineralization in chondrules, CAIs and matrices, including phyllosilicates, magnetite, Ni-rich metal and sulfides, Ca-Fe-rich silicates, ferrous olivine (Fa_{30-50}), nepheline, and sodalite [1]. While the importance of metasomatism is widely recognized, the site of alteration—solar nebula or asteroid regolith—has remained highly controversial [2]. Hua and Buseck [3] described fayalite (Fa_{90-100}) in association with magnetite and sulfides in the CV3 chondrites Kaba and Mokoia and concluded fayalite formed by high-temperature reactions between magnetite and SiO gas in the nebula. Krot et al. [4–6], however, showed that in Type I chondrules in Kaba and Mokoia fayalite and Ca-, Fe-rich pyroxenes replace magnetite nodules and coexist with phyllosilicates. They inferred that magnetite, phyllosilicates, fayalite, and Ca-Fe-rich pyroxenes formed sequentially at low temperatures (<300°C) during fluid-rock interaction on the CV3 asteroid. In order to elucidate the time scale and site of alteration, we investigated the Cr isotope composition of fayalite in Type I chondrules in Mokoia to search for evidence of ^{53}Mn ($\tau_{1/2}$ = 3.7 Ma).

Fayalite (30–100 µm in size) in Type I chondrules in Mokoia is compositionally uniform (Fa_{99-100}) with 0.2–0.9 wt.% MnO; Cr_2O_3 is below electron microprobe detection limits (<0.02 wt.%). The distribution of fayalite within opaque nodules and the presence of relic kamacite inside forsterite phenocrysts show that fayalite formed by replacement of magnetite, which had earlier replaced metal. The fayalites analyzed here are blocky to subhedral grains located along the boundary between the host chondrule and its igneous rim. Fayalites frequently contain small magnetite and sulfide inclusions and are corroded by or associated with Ca-, Fe-rich pyroxenes.

Four fayalite grains in three chondrules were analyzed for Cr isotopes and in contrast to data reported by Wadhwa et al. [7], all show large excesses of ^{53}Cr correlated with the respective Mn/Cr. A distinguishing feature of these fayalites is the remarkably low Cr; fayalite in chondrule 8 with δ^{53}Cr = 1307‰, e.g., contains <50 ppbw Cr_2O_3. The correlation between δ^{53}Cr and Mn/Cr indicates formation of Mokoia fayalite while ^{53}Mn was extant and the slope of a line fitted to the data, passing through normal Cr at Mn/Cr = 0, yields the initial ^{53}Mn abundance, $^{53}Mn/^{55}Mn = (2.3 \pm 0.2) \times 10^{-6}$ (Fig. 1).

The evidence for live ^{53}Mn enables us to determine the time scale of fayalite formation. If we assume $^{53}Mn/^{55}Mn = 4.4 \times 10^{-5}$, inferred from studies of Allende CAI [8], indicates the local solar system initial abundance of ^{53}Mn, these Mokoia fayalites formed ~16 Ma after crystallization of Allende CAI. This time scale is substantially longer than estimates of the lifetime of the hot solar nebula and we infer that fayalite and coexisting Ca-Fe-rich pyroxenes formed in an asteroidal environment, not in the solar nebula. The Mn-Cr chronology suggests metasomatic alteration on the CV3 parent asteroid was contemporaneous with aqueous activity on the CI parent body [9,10] and commenced within a few Ma of planetary accretion.



References: [1] A. N. Krot et al. (1995) *Meteoritics,* 30, 748; [2] *LPI Tech. Rpt.* 97-02 (1997); [3] X. Hua et al. (1995) *GCA, 59,* 563; [4] A. N. Krot et al. (1997) *LPI Tech. Rpt.* 97-02, [5] A. N. Krot et al. (1998a) *Meteoritics & Planet. Sci.,* in press; [6] A. N. Krot et al. (1998b) *Meteoritics & Planet. Sci.,* in press; [7] M. Wadhwa et al. (1998) *LPS XXIX,* abstract #1484; [8] J-.L. Birck and C. J. Allègre, *Nature, 331,* 579 (1988); [9] M. Endress et al. (1996) *Nature, 379,* 701; [10] I. D. Hutcheon and D. L. Phinney (1996) *LPS XXVII*, 577.

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SILICA-BEARING OBJECTS IN BALI (CV3): A NOVEL TYPE OF INCLUSION IN CARBONACEOUS CHONDRITES. M. A. Nazarov[1], G. Kurat[2] and F. Brandstätter[2]; [1]Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow, 117975, Russia, [2]Naturhistorisches Museum, Postfach 417, A-1014 Vienna, Austria.

Introduction: Silica-bearing objects are common accessory constituents of ordinary and enstatite chondrites [e.g., 1]. Their origin is not clear and nebular and parent body processes have been proposed for the formation of these objects [1–6]. Free silica is extremely rare in carbonaceous chondrites and was so far found only in Murchison [7] and in a carbonaceous clast from the Erevan howardite [8]. Here we report on abundant silica-rich objects in a dark inclusion (DI) from the Bali (CV3) carbonaceous chondrite. This is a new type of silica-bearing objects in chondritic matter. The origin of these objects could be related to nebular metasomatic alteration of CAIs.

Results: The Bali specimen I 2662 (Naturhistorisches Museum, Vienna) contained a dark inclusion of about 6 × 5 × 4 mm dimension which is highly enriched in magnetite as compared the Bali host (in which pentlandite and pyrrhotite are the most abundant opaque phases). The matrix of the DI is porous and consists mainly of intergrowths of platy olivines rich in FeO (30 wt%) and NiO (2 %) and magnetite. This inclusion also contains about 1 vol% of silica-rich objects which resemble CAIs in their appearance (Fig. 1). The small objects are rounded and have dimensions of 10–20 µm. The larger objects are elongated and their sizes range from about 20 × 30 µm to 10 × 50 µm. The objects have a concentric structure with a core of mainly very fine-grained, dense silica. This silica has a variable chemical composition and is rich in minor elements (Al_2O_3: 0.2 wt%, FeO: 2.5, MgO: 0.6, NiO: 4.0, CaO: 0.3, and Na_2O: 0.1). In particular, the high contents of NiO (3.0–8.0 wt%) are remarkable. Some places are rich in Al_2O_3 (up to 2.5%) or P_2O_5 (up to 1.4%). Minor phases are wollastonite, andradite and Ca-rich pyroxene. A Ni-rich silicate (up to 30% NiO) was also found but it is too small for identification. One object contains a small (3 µm) grain of larnite associated with wollastonite and andradite.

Beside silica-rich objects there are wollastonite-rich inclusions in the Bali DI which are up to 70 µm in size and have a rounded or irregular shape. They consist mainly of relatively coarse-grained wollastonite that contains rare minute grains of diopside, hedenbergite and andradite. Some of the inclusions contain also free silica.

Silica-rich and wollastonite objects are always covered by two rims (each about 5 µm thick). The inner layer is made of hedenbergite whereas the outer layer consists of salite or diopside. Sulfur and Ni are often present in the rims.

Discussion: The free silica is certainly of secondary origin and out of equilibrium with the chondritic, olivine-rich matrix. The shapes and the presence of Ca phases (including diopside) and rims suggest CAI precursors. The sequence of alteration events is not clear. The conditions must have been highly oxidizing (Fe, Mn, Ni metasomatism of olivine and pyroxene, formation of andradite, hedenbergite, magnetite). Free silica is dense and had to be added to the inside of the objects. It is not clear why SiO_2 was deposited there. A possible hint is given by wollastonite which possibly formed from $CaCO_3$ by reaction with SiO_2. Thus, it is possible that reactive Ca-rich phases of pre-existing CAIs were carbonatized first and then silicified. Because there are no traces of Si mobility in the DI matrix which consists mainly of olivine, these metasomatic reactions must have taken place before accretion.

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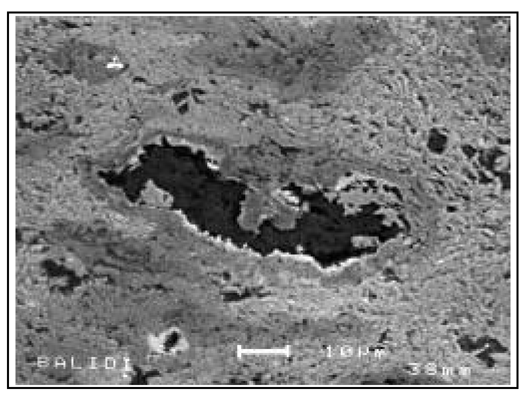

Fig. 1. SiO_2-rich object in a DI from Bali (CV3). Silica (dark), hedenbergite (light inner rim), diopside (dark outer rim) in olivine matrix.

THERMAL METAMORPHISM OF CARBONACEOUS CHONDRITES: SIMULATIONS AND REALITY.

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Introduction: Prior data obtained petrographically, and by RNAA (especially for highly mobile Cs, Se, Ag, Te, Zn, In, Bi, Tl and Cd), oxygen isotope mass spectrometry and spectral reflectance indicate that Y-82162 (CI) and B-7904 and Y-86720 (both CM) experienced thermal metamorphism in their parent bodies [1-5]. From comparisons with Murchison (CM2) heated for one week under conditions simulating open-system thermal metamorphism in parent bodies [6], data for these 3 Antarctic chondrites were consistent with alteration temperatures of 600-700EC [1]. Spectral reflectance data from these samples suggested that surfaces of C-, G-, B- and F-asteroids represent mixture of thermally metamorphosed, carbonaceous chondrite-like interior material excavated by impacts [4,5].

More recently [7], RNAA data for carbonaceous chondrites with min.-pet., oxygen isotopic and/or spectral reflectance properties suggestive of thermal metamorphism, led to identification of 7 additional such chondrites (all from Antarctica) altered under open-system conditions. At least one other meteorite, Y-793321, was altered under conditions closed to volatile-loss [7]. Since we had not previously studied by RNAA samples heated under closed conditions (in which oxygen isotopic and spectral reflectance properties are altered [3,8]) we carried out such a study.

Experimental: We heated 50-60 mg Ivuna (CI1) samples in separate sealed ampoules (i.e. closed system) for 1 week at 100EC increments from 300-600EC. We also included in the 600EC heating run, two Murchison samples - one in a sealed ampoule, the second in an ampoule open to the ambient muffle atmosphere - to compare with our earlier results [6]. After quenching, the ampoules were opened and transferred to evacuated, sealed quartz vials and irradiated (with monitors) for 6 days at a flux of 8×10^{13} n/cm^2 s in the Univ. of Missouri Research Reactor. We analyzed samples and monitors by our usual RNAA techniques [9]. Elements determined in addition to the 9 highly mobile ones listed above are U, Co, Au, Sb, Ga and Rb.

Results and Discussion: At present we have results only for the four heated Ivuna samples. By meeting time, we will have results for unheated Ivuna, the 2 heated Murchison samples and additional Antarctic carbonaceous chondrites suspected of thermal metamorphism in their parent bodies.

With but one exception, Tl in Ivuna heated at 600EC, all elements in the four samples heated under closed conditions were quantitatively retained. The exceptional Tl datum was lowered by one order of magnitude. These results are in contrast with earlier ones for Murchison heated under open-system conditions to the same temperatures [6], in which Cd is significantly lost at 500EC and In, Bi, Tl and Cd are lost at 600EC.

Our results confirm our earlier assumption that carbonaceous chondrites can be heated at substantial temperatures under conditions such that highly mobile elements are not generally lost. Results for additional carbonaceous chondrites will be reported at the meeting.

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EVIDENCE FOR THERMAL ALTERATION IN ASUKA 881655 CHONDRITE. M. S. Bell[1], M. E. Zolensky[2], and S. V. Yang[1], [1]Mail Code C23, Lockheed Martin ESS, 2400 NASA Road 1, Houston TX 77058, USA (msbell@ems.jsc.nasa.gov), [2]Mail Code SN2, NASA Johnson Space Center, Houston TX, USA.

Introduction: Asuka 881655 is a severely brecciated carbonaceous chondrite which is reported to exhibit significant depletion of the most thermally-mobile trace elements consistent with open-system loss during extended asteroidal heating [1]. Here we report major element compositions for olivines, pyroxenes, sulfides, and what we interpret as heated phyllosilicates. Verification that these latter materials were indeed once phyllosilicates would permit us to determine conditions under which asteroidal aqueous alteration and subsequent metamorphism occurred.

General Mineralogy: This meteorite is severely brecciated, but appears to be monomict. Chondrules, CAI, and lithic clasts are clearly present, other materials are of doubtful nature, probably due to the extreme range of alteration processes they experienced. In general, olivine in all components varies from Fo_{44} to Fo_{85}, and often contains excess aluminum. In one clast olivine is found intergrown with bladed magnetite, a growth habit we have not seen before. These magnetites have apparent relict anhedral Fe-Ni sulfide inclusions, consistent with the magnetite having replaced pyrrhotite, as previously observed in the Kaidun chondrite [2]. Pyroxene compositions range from En_{28-52} Wo_{34-57} Fs_{1-20} and are also associated with Fe-Ni sulfides. Low calcium pyroxenes (En_{87} $Wo_{<1}$) are present as fractured grains intergrown with a fine-grained Ca-Al rich phase, probably heated phyllosilicate. Low-Ca pyroxenes are surrounded by haloes of Fe-Ni sulfides. Olivine and pyroxene compositions are consistent with classification as CV chondrites.

Individual clasts: The clasts within this meteorite are mainly of very small size, indicating a high-energy regolith environment. Three clasts which display textures suggesting a wide variety of thermal alteration effects have been examined in detail. A large clast of high-Ca pyroxene ($En_{28}Wo_{52}$ with considerable Al; ~200 µm in size), exhibits numerous sinuous cracks and voids, and abundant anhedral Fe-Ni sulfide inclusions- some of which follow fractures. The boundary between the pyroxene grain and the surrounding matrix is sharp and fractures follow this interface. This clast is interpreted to be a chondrule which was altered to phyllosilicate (probably saponite, based upon the high Al content), then thermally metamorphosed to pyroxene.

Less altered in appearance is an ~100µm CAI consisting of pyroxene (En_{41} $Wo_{.52}Fs_6$) surrounded by a layer of Al-rich spinel. The size of the pyroxene areas varies (~10µm) although the Al-rich layers are consistently ~5µm wide. Patches of irregularly shaped Fe-Ni sulfides ranging from < 1µm to >100µm are found in the center of the inclusion and fill fractures extending to its margins. Fractures also surround the inclusion.

Possibly the most altered inclusion we studied is an intergrowth of bladed magnetite and massive olivine (Fo_{58}). The magnetite crystal habit has not been previously observed in carbonaceous chondrites and is reminiscent of acicular pyrrhotites incipiently replaced by magnetite in the CM1 lithology in Kaidun. Elemental maps of the inclusion reveal ~1µm relict Fe-sulfide blebs in the magnetite interstices, interpreted to be residual pyrrhotite. We suggest that the precursor pyrrhotite formed from heating of phyllosilicate to produce Fe-Ni sulfides and olivine, and was subsequently oxidized and replaced by magnetite.

The meteorite is yet another Antarctic carbonaceous chondrite (probably CV), which was heated on its parent asteroid. It is interesting that these have all been found in some of the younger Antarctic meteorite accumulations.

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EXPERIMENTAL SHOCK METAMORPHISM OF THE MURCHISON CM CARBONACEOUS CHONDRITE.

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Carbonaceous chondrites are expected to respond to high-shock compression differently from other types of meteorites, because of their intrinsic porous nature and high volatile contents. However, highly shocked carbonaceous chondrites are rare [1], and thus how they respond to high shock pressure is not well known. In order to understand the shock history of carbonaceous chondrites, we have carried out a series of shock-recovery experiments of the Murchison CM chondrite using a single-stage propellant gun. The Murchison samples were shocked at 7, 11, 21, 26, 28, 30, 34, 36, and 49 GPa. All the known CM chondrites have been estimated to be shock stage S1-S2 (<5-10 GPa) [1], thus the pressures higher than 10 GPa have never been experienced by these meteorites.

Impact at 7-30 GPa: Chondrules are flattened nearly perpendicular to the compression axis in the pressure range 7–30 GPa. The mean aspect ratio of chondrules increases from 1.17 to 1.57 roughly in proportion to the intensity of shock pressure in the pressure range <26 GPa. This indicates that chondrule flattening and foliation are important characteristics of shock compression for CM chondrites and that the mean aspect ratios of chondrules can be used for quantitative estimates of shock intensities in this pressure range. However, at 26–30 GPa, chondrules do not show any further flattening but show increasingly higher variations in aspect ratio and orientation. Increasing proportions of olivine and pyroxene in chondrules are finely fractured with increasing shock pressure, and almost all olivines and pyroxenes are fractured with subgrains of <5 µm at 30 GPa. Local melting occurs as melt veins and pockets at 21–30 GPa. The melts are mostly produced from the matrix but consistently more enriched in Fe, S, and Ca. The melts contain tiny spherules of Fe-Ni metal and sulfides and abundant bubble-like voids. At 21 GPa, thin, subparallel fractures begin to form in the matrix in directions perpendicular to the compression axis. Their number density increases greatly at 26 GPa, and they extend in high density throughout the matrix at 30 GPa. Thus, at 26–30 GPa, the sample is increasingly comminuted and becomes fragile.

Impact at 34-49 GPa: The samples are strongly flattened and taper off toward the peripheries, where melted materials fill fractures produced in the stainless steel containers. At 34 and 36 GPa, the samples are converted to an assemblage of rounded to irregularly-shaped blocks of 50–200 µm in dimension, thus exhibiting a breccia-like texture. They are found to be even more fragile than the 30-GPa sample. Most chondrules are disintegrated and show no preferred orientations. Incipient melts occur randomly on a scale of 10–50 µm. Thus the matrix becomes a complex mixture of incipient melts and fine grains. At 49 GPa, the matrix is totally melted, and the general texture becomes chaotic; isolated grains of olivine and pyroxene are scattered in the melts. Some olivine grains are partially melted. The melts contain bubble-like voids that are much larger in size (50–200 µm in diameter) than those in the samples shocked at lower pressures, which indicates that much intenser evaporation and gas volume expansion took place in this sample.

The great increase in degree of comminution of the Murchison sample, thus in degree of fragility, and the simultaneous generation of strong expansive force at 25–35 GPa testify the hypothesis of Scott et al.. [1] that the volatile-rich carbonaceous chondrites shocked above 20–30 GPa escaped from the parent body on pressure release and formed particles that are too small to survive as meteorites.

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CHONDRITE CARBONACEOUS MATERIALS: TERRESTRIAL ANALOGS AND THEIR SHOCK MODIFICATION. A. V. Korochantsev and D. D. Badjukov, Vernadsky Institute, Kosygin Street 19, 117975 Moscow, Russia.

Structural and chemical parameters of two-dimentionally ordered natural bitumens as terrestrial analogs of chondritic organic material (OM) [1] are compared here with those of chondritic OM (Table). When comparing, we use data on chondritic OMs presented as residues after organic solvent extraction and HCl/HF treatment. This processing is known to partly disrupt OM [2]. In the case of bitumens, we deal with the original OM. The OM of Orgueil (CI1) is especially sensitive to a treatment, for example, HCl-attack results to loss of almost 50% of the total carbon budget [3]. Taking it into account and based on the Table data we suggest that the original OM of this chondrite resembles an *asphaltite/low kerite*. As seen in Table 1, Murchison (CM2) residues are similar to *high kerites/low anthraxolites* in both structural and chemical parameters. These parameters of the Allende (CV3) residues are close to those of *medium/high anthraxolites*.

Carbonaceous chondrites are breccias. Their parent bodies are asteroids whose surface material was affected by impacts. We simulated [4] possible effects of impact-induced modifications of OM on a sample of a natural solid bitumen—*asphaltite* (a probable analog of CI chondrite OM). In our laboratory experiments, the asphaltite was shock-loaded at pressures of from 17 to >60 GPa. The asphaltite shock-loaded up to 27 GPa didn't show significant structural and chemical changes as compared to the initial asphaltite. Runs at the pressure interval of from 27 to 60 GPa were not carried out. At 60 GPa, the asphaltite became similar to a *high kerite/low anthraxolite* (a probable analog of CM chondrite OM), and at >60 GPa, became similar a *medium/high anthraxolite* (a probable analog of CV chondrite OM) (Table).

Our data are consistent with experiments [5] which showed incipient to complete water loss from serpentine at shock pressure of from 20 to 60 GPa, respectively. Thus, under impacts CI and CM chondrites should preserve H-rich OM and phylosilicates up to 60 GPa. A higher shock pressure should lead to an assemblage of H-poor OM and unhydrous silicates.

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Table 1.

	XRD				HRTEM/SAED[1]
	Ordered aromatics	Ordered aliphatics[2]	Ordered aromatics	Ordered aliphatics[2]	Total carbonaceous matter
	Experimental data		***Natural bitumens***		**Meteorite organic residues**
	Initial asphaltite		*Asphaltites/low kerites*		Orgueil (CI1)
Fraction of ordered matter	0.25	0.75	0.0-0.3	0.7-1.0	
d(002)	3.65Å		3.55-3.7Å		3.8Å (90%), 3.6Å [7]
Lc	7Å		6.0-8.5Å		up to 15Å [7]
dγ		5.15Å		4.7-5.3Å	
H/C(at.)	1.25		1.63-0.84 [6]		0.76 [8]
	Asphaltite shock-loaded at 60 GPa		*High kerites/low anthraxolites*		Murchison (CM2)
Fraction of ordered matter	0.37	0.63	0.2-0.4	0.6-0.8	
d(002)	3.5Å		3.45-3.6Å		3.57Å [7]
Lc	14.5Å		8-17Å		20Å [7]
dγ		4.84Å		4.7-4.9Å	
H/C(at.)	0.44		1.22-0.38 [6]		0.7 [8]
	Asphaltite shock-loaded at >60 GPa		*Medium/high anthraxolites*		Allende (CV3)
Fraction of ordered matter	0.7	0.3	0.55-0.9	0.1-0.45	
d(002)	3.4Å[3]		3.4-3.47Å		3.5Å [7]
Lc	26.5Å[3]		13.5-31Å		30Å [7]
dγ		4.15Å		4.1-4.65Å	
H/C(at.)	0.11		0.03-0.4 [6]		0.135-0.46 [9]

[1] HRTEM/SAED data appear to be systematically higher in d(002) values than the XRD data, may be due to the fact that HRTEM/SAED technique doesn't distinguish between the ordered aliphatics and the aromatics.

[2] Mostly aliphatics; some single aromatic rings, olefinic, and O-containing groups may be embedded in aliphatic structures.

[3] There is a minor graphite peak (d(002)=3.35 Å, Lc=190 Å). Compare to Dimmitt (H3,4) - d(002)=3.38Å, Lc=80Å [9].

PLANAR DEFECTS IN MATRIX OLIVINES FROM THE OXIDIZED SUBGROUP OF THE CV3 CARBONACEOUS CHONDRITES: A GROUP CHARACTERISTIC. L. P. Keller, MVA Inc. 5500/200 Oakbrook Parkway, Norcross GA 30093, USA (lkeller@mvainc.com).

Fine-grained olivine is the major constituent in the matrices of the C3 carbonaceous chondrites, and occurs in several different morphologies including high-aspect ratio platelets, equant grains, and anhedral grains. Olivine compositions cluster around Fo_{50}, but the degree of *matrix* equilibration varies widely from essentially unequilibrated compositions in Kaba and Mokoia, to highly equilibrated olivines in Allende and Grosnaja. Transmission electron microscopy (TEM) studies of CV3 matrices (Mokoia, Kaba, Bali, Allende, Grosnaja) have shown that these members of the oxidized subgroup all contain a population of olivine grains with a distinctive microstructure: planar defects along the olivine (100) planes [1–4]. These microstructures are rare or absent in matrix olivines from the reduced subgroup CV3 chondrites Vigarano and Leoville [4, 6].

TEM images of matrix olivines show that they typically contain a high density of planar features that produce strong streaking along a* in selected-area electron diffraction patterns. Streaking along the other orthogonal axes (b* and c*) is not observed. High-resolution TEM images of the planar features (Figure 1) show lattice offsets (arrows) along (100), which indicates that these are stacking faults and not lamellae of a second phase. These planar defects however, do serve as energetically favorable sites for the nucleation and epitaxial growth of saponite and magnetite in aqueously altered CV3 chondrites (e.g. Kaba, Bali, Mokoia, and Grosnaja) [1–4]. It is clear that in some of the CV3 chondrites, the development of the planar defects pre-dates the formation of the aqueous alteration phases [3]. Furthermore, these olivine defects are also common in the anhydrous matrix of Allende.

Because lattice offsets are associated with the planar features, it was proposed that the defects resulted from deformation on the CV parent body [3]. There are however, several ambiguities in this interpretation. First, not all matrix olivines contain these defects, so if the microstructure is produced by shock, than the defects were likely formed in this group of olivine grains prior to accretion. Second, olivines in some deformed CV3 meteorites (Leoville, for example) do not show the distinctive (100) planar defects seen in the oxidized group [5, 6]. However, olivines with (100) planar defects are interpreted as shock features in Chassigny olivines [7] . This latter point implies that strain rates may be important in the formation of the (100) defects. Finally, we speculate that the planar features could also be crystal growth defects, but this hypothesis would also require the preaccretional formation of the defects. Regardless of their genesis, these unique defects appear to be another characteristic feature of the oxidized subgroup of the CV chondrites.

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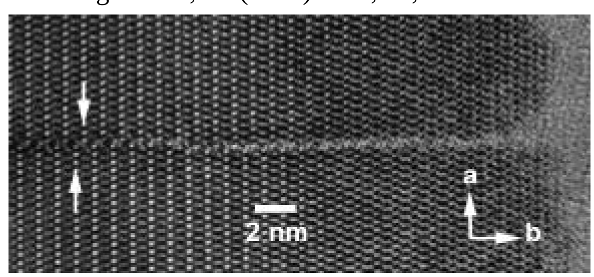

Fig. 1. A high-resolution TEM image of a (100) planar defect in a matrix olivine grain from the Kaba CV3 chondrite.